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Observations of trash in the deep tropical Atlantic and Caribbean Sea

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ABSTRACT

Evidence of anthropogenic impacts on deep-ocean systems is frequently observed, even upon the first explorations of these remote environments. One of these impacts comes from marine debris, trash that is dumped or transported into the deep ocean. Understanding the abundance and distribution of marine debris is critical to identifying holistic changes and feedbacks that influence the health and sustainability of ocean ecosystems. Here, we document widespread plastic, metal, and glass debris in deep waters of the tropical Atlantic and Caribbean Sea, observed by remotely operated and human occupied submersibles. Trash was observed from depths 250 to >6000 m. A total of 139 pieces of debris were found, including a ladder, clothing, cans, cutlery, single-use sauce packages, and a parachute. These findings further illustrate the extent of debris pollution in deep waters and the need to understand the impact of debris pollution on sustainability in Earth's largest habitat.

Con frecuencia se observan evidencias de que los desechos antropógenos afectan a los sistemas oceánicos profundos, incluso en las primeras exploraciones de estos ambientes remotos. Uno de estos impactos viene de desechos marinos, basura que es tirada o transportada a los oceánicos profundos. Entendiendo la abundancia y la distribución de los desechos marinos es crítico para identificar cambios holísticos y comentarios que influencian la salud y la sostenibilidad de los ecosistemas oceánicos. En esta investigacion documentamos una extensa variedad de desechos como: plásticos, metal y vidrio en los ecosistemas oceánicos del Atlántico tropical y el Mar Caribe, observados por vehiculos robóticos controlados remotamente y ocupados por humanos. La basura fue observada desde las profundidades de 250 a más de 6000 m. Se encontraron un total de 139 piezas de desechos, incluyendo una escalera, ropa, latas, cubiertos, paquetes de salsa de un solo uso y un paracaídas. Estos descubrimientos ilustran la gran relevancia de la contaminación por los desechos en aguas profundas y la necesidad de comprender el impacto de dicha polución por desechos en la sostenibilidad en el hábitat más grande de la Tierra.

1. Introduction

Human activities impact all habitats on Earth. These effects extend even to those environments that are considered the most remote, such as the deep ocean. Deep-sea ecosystems are under threat from anthropogenic stressors such as climate change, ocean acidification, mineral exploitation, and waste disposal (e.g., Ramirez-Llodra, 2020; Ramirez-Llodra et al., 2011; Sweetman et al., 2017), but the extent and magnitude of that threat is not yet well-defined. Waste has been actively dumped in the deep oceans for centuries because disposal in this

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ecosystem was once seen as a convenient and ethical alternative to disposal on land. Common disposals into the deep come in the form of sewage, dredge spoils, pharmaceuticals, radioactive waste, chemical contaminants such as chlorofluorocarbons (CFCs) and polycyclic aromatic hydrocarbons (PAHs), wrecks, munitions, and clinker (an ash-like product formed from the burning of coal) (e.g., Ramirez-Llodra et al., 2011). Although the intentional dumping of multiple kinds of waste was banned in 1972 (London Convention, 1972), floating trash and other types of marine litter from illegal disposal, lost fishing gear, and coastal inputs continue to sink to the deep seafloor.

Marine litter is abundant and widespread, with evidence of trash in the deep oceans mounting globally in concert with increasing observations. In the north Atlantic Ocean and Mediterranean Sea, imaging surveys using remotely operated vehicles (ROVs), submersibles, and towed camera systems, along with direct trawl sampling revealed litter at depths down to 4500 m (Pham et al., 2014; Quattrini et al., 2015). Debris density can be high, for example, reaching 4.0 ± 1.8 kg of litter per hectare in the Western Mediterranean Sea (Pham et al., 2014). Plastic, glass, clinker, metal, and discarded fishing gear are all common forms of litter found in waters throughout the deep ocean (Ramirez-Llodra et al., 2013). In a six-year study in the Barents Sea, marine debris was found in 301 of 2265 pelagic trawls surveyed, 624 of 1860 benthic trawls, and an additional 784 pieces of floating marine debris were observed (Grøsvik et al., 2018). At the HAUSGARTEN observatory at 2500 m depth in the Arctic Ocean, marine litter has been shown to be increasing in the deep ocean in recent years, based on analyses from 2002 to 2014 (Tekman et al., 2017). In the northeastern United States, ROV surveys found 140 pieces of marine litter on 31 dives from depths 494 to 3271 m (Quattrini et al., 2015). A survey by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) found 3425 observed pieces of anthropogenic debris on 5010 deep-sea submersible and remotely operated vehicle dives in the Pacific, Atlantic, and Indian Oceans (Chiba et al., 2018). The deepest of these observations was a plastic bag seen by the *ROV Kaiko* in 1998 at 10,898 m in the Mariana Trench (Chiba et al., 2018). From the JAMSTEC database, Chiba et al. (2018) estimated litter densities at depths 1085–6037 m to be 11 and 342 items per km^2. In Monterey Canyon in the northeastern Pacific, a survey of ROV video collections from over a 22-year period found 1537 observations of marine litter, reaching depths of up to 3971 m (Schlining et al., 2013). In the central and western Pacific Ocean, the National Oceanic and Atmospheric Administration (NOAA) Ocean Exploration dives with *Seirios* and *Deep Discoverer* remotely operated vehicles (ROVs) documented debris including metal, glass, plastic, and rubber from depths 150–6000 m, finding the highest debris densities off American Samoa and the main Hawaiian Islands (Amon et al., 2020). In the deep ocean, plastic debris is of particular concern due to its long-lasting presence, as plastics are predicted to remain in these habitats for hundreds to thousands of years (e.g., Amon et al., 2020; Ramirez-Llodra et al., 2011), although more research is necessary to determine persistence times across materials (Ward et al., 2019). The multitude and geographic scale of marine trash observations—from surface waters to the deepest ocean depths—demonstrate the prevalence of pollution in the deep ocean.

Due to the immense scale of deep-sea habitats and the challenges of studying these environments, significant gaps remain in our understanding of the distribution and abundance of marine litter. Documenting instances of marine debris remains an important undertaking to understand distribution patterns and temporal dynamics of litter in the deep sea and to inform management efforts (e.g., Amon et al., 2020). Here, we report marine litter that was observed opportunistically on five expeditions by the remotely operated vehicles *Seirios*, *Deep Discoverer*, and *Global Explorer* and the submersible *Alvin* in deep waters surrounding Puerto Rico in the tropical Atlantic Ocean and Caribbean Sea (Candio et al., 2022; Candio et al., 2023; Kennedy et al., 2015; Sowers et al., 2020; Wagner et al., 2019). These findings add to a growing body of evidence that illustrates the scale of the marine litter problem and calls for the deep ocean to be included in pollution mitigation efforts.

2. Methods

2.1. Video collection

To determine the abundance and distribution of trash in the deep waters of the tropical Atlantic and Caribbean Sea, we analyzed videos collected on five expeditions to the region from 2015 to 2022. Three of these expeditions were led by the NOAA Ocean Exploration program, "Océano Profundo 2015: Exploring Puerto Rico's Seamounts, Trenches and Troughs" (EX1502, Leg 3, Kennedy et al., 2015), "Océano Profundo 2018: Exploring Deep-Sea Habitats off Puerto Rico and the U.S. Virgin Islands" (EX1811, Sowers et al., 2020; Wagner et al., 2019), and "Voyage to the Ridge" (EX2206, Candio et al., 2022, 2023). These expeditions sailed aboard the NOAA Ship *Okeanos Explorer* and collected video using the two-bodied ROV platform of *Deep Discoverer* and *Seirios*. This telepresence-enabled deep-sea exploration program enables scientific discovery and communication to broad audiences, providing valuable open access data. Further details on the operations of ROV *Deep Discoverer* and details on the NOAA Ocean Exploration program are described by Kennedy et al. (2019). Video from these expeditions was accessed via SeaTube (Ocean Networks Canada, https://data.oceannetworks.ca/ExpeditionManagement), using methods described by Gerringer et al. (2023). The fourth expedition, "Illuminating Biodiversity off of Puerto Rico" (NF2202), sailed aboard the NOAA Ship *Nancy Foster* and observed the seafloor with the ROV *Global Explorer*. On the fifth expedition, the human occupied vehicle (HOV) *Alvin* was used to survey deep waters in and around the Puerto Rico Trench aboard the RV *Atlantis* (AT50-02, Science Verification Expedition of refitted submersible). Additional details on video collection on the AT50-02 expedition are described by Peoples et al. (2024).

Video Analysis. For each expedition, dive videos were watched by one to two researchers and manually annotated. Latitude, longitude, and depth were recorded for each observation of human-produced trash on the seafloor. Only objects that could be confidently described as debris were recorded. Each piece of debris was identified to the most specific available category (fishing gear or other debris), and material (plastic, metal, glass, fabric, wood, mixed) was classified visually where possible. Some items were identified as not being natural in origin but were not able to be classified to a specific material type. Artificial coloration, printed patterns, and sharp edges were used to distinguish anthropogenic debris from natural materials. We took a conservative approach to identifying material, with items that were potentially anthropogenic, but possibly natural not being counted in the present dataset. However, it is still possible that some items classified here as unknown materials could be natural in origin. A total of twenty-five dives were analyzed for instances of trash, four by the *HOV Alvin,* three by the *ROV Global Explorer*, and 19 by the *ROV Deep Discoverer* (Table 1).

2.2. Data analysis

Data were analyzed using the statistical programming platform R (R Core Team, 2024). Observations were mapped using the *marmap* package, with bathymetry data from NOAA National Centers for Environmental Information (NCEI, Pante and Simon-Bouhet, 2013). Observations were binned by 1000 m depth increments. The composition of materials across dive depth was compared using an analysis of similarity (ANOSIM) in the package *vegan* (Oksanen et al., 2016). For dives on NOAA Ocean Exploration expeditions, seafloor observation area was estimated using NOAA's ROV Deep Discoverer dive track GIS product (https://noaa.maps.arcgis.com/home/item.html?id=f524a41748af480abb6844b084a2c649). These tracks were truncated to between the recorded on and off bottom locations. Then, using the *sf* package in R (Pebesma, 2018), a buffer of 5 m on each side of the dive track was used to calculate the area observed by the ROV. See Kennedy

Table 1
Observations of marine debris in deep waters off Puerto Rico, Atlantic Ocean and Caribbean Sea. Date and observation start time are shown in UTC. Video on expeditions EX1502L3, EX1811, EX2206, and NF2202 was collected by ROV and by HOV on expedition AT50-02.

Expedition	Dive Site	Dive #	Date	Time	Latitude (°N)	Longitude (°W)	Depth (m)	Material	Description
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	15:07:18	18.86017	−66.8111	4058.3	Metal	Coke Can
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	15:20:48	18.86030	−66.81122	4050.8	Fabric	Denim
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	15:30:48	18.86019	−66.81135	4038.4	Metal	Budweiser Can
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	15:56:18	18.85984	−66.81192	4007.2	Metal	Metal Can
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	16:20:48	18.85992	−66.81238	3977.1	Plastic	Plastic
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	17:10:18	18.85961	−66.81335	3902.5	Metal	Shredded Metal
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	17:45:48	18.85962	−66.81391	3781.6	Glass	Glass
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	18:31:48	18.85933	−66.81565	3667.4	Metal	Coke Can
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	18:32:48	18.85938	−66.81559	3662.0	Metal	Aluminum Can
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	19:00:18	18.85925	−66.81687	3573.8	Plastic	Plastic Bucket
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	19:28:48	18.85928	−66.81739	3525.1	Unknown	Unknown
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	19:41:18	18.85902	−66.81787	3501.5	Plastic	Plastic Knife
EX1502L3	Arecibo Amphitheater	1	10-Apr-2015	20:33:18	18.85919	−66.819	3363.7	Wood	Wooden Post
EX1502L3	Septentrional Fault	2	11-Apr-2015	16:32:29	19.00718	−67.72726	3671.7	Mixed	Vinyl on Wood
EX1502L3	Septentrional Fault	2	11-Apr-2015	16:37:59	19.00691	−67.7269	3673.0	Plastic	Plastic
EX1502L3	Septentrional Fault	2	11-Apr-2015	16:45:29	19.00654	−67.72716	3669.9	Plastic	Plastic
EX1502L3	Septentrional Fault	2	11-Apr-2015	16:45:59	19.00649	−67.72715	3670.3	Plastic	Plastic
EX1502L3	Septentrional Fault	2	11-Apr-2015	16:50:29	19.00625	−67.72693	3671.4	Plastic	Plastic Cups
EX1502L3	Septentrional Fault	2	11-Apr-2015	16:52:59	19.00592	−67.72699	3671.1	Plastic	Plastic Bag
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:00:59	19.00533	−67.72694	3670.4	Unknown	Unknown
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:04:29	19.00511	−67.72681	3670.3	Plastic	Plate
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:05:59	19.00507	−67.72698	3670.7	Plastic	Plastic
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:12:29	19.00451	−67.72695	3668.6	Plastic	Cardboard and Plastic
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:24:29	19.0033	−67.72682	3660.6	Unknown	Unknown
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:27:29	19.00322	−67.72676	3660.1	Plastic	Plastic
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:45:59	19.00192	−67.72683	3636.3	Plastic	Plates
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:54:29	19.00149	−67.72674	3618.2	Plastic	Plate
EX1502L3	Septentrional Fault	2	11-Apr-2015	17:56:29	19.0013	−67.72675	3613.2	Unknown	Container
EX1502L3	Septentrional Fault	2	11-Apr-2015	18:17:29	19.00052	−67.72673	3573.7	Plastic	Coffee Creamer
EX1502L3	Septentrional Fault	2	11-Apr-2015	18:59:59	18.99812	−67.72657	3425.0	Unknown	Unknown
EX1502L3	Septentrional Fault	2	11-Apr-2015	19:27:59	18.99662	−67.72661	3329.7	Metal	Steel Can
EX1502L3	Septentrional Fault	2	11-Apr-2015	19:55:59	18.99494	−67.72625	3221.4	Metal	Aerosol Can
EX1502L3	Septentrional Fault	2	11-Apr-2015	19:58:59	18.99487	−67.72629	3212.2	Unknown	Bottle
EX1502L3	Septentrional Fault	2	11-Apr-2015	20:03:59	18.99458	−67.72626	3194.9	Unknown	Unknown
EX1502L3	Pichincho	3	12-Apr-2015	11:43:25	18.37801	−67.77924	607.9	Unknown	Unknown
EX1502L3	Pichincho	3	12-Apr-2015	13:11:25	18.37806	−67.77884	601.5	Glass	Glass Bottle

(continued on next page)

Table 1 (*continued*)

Expedition	Dive Site	Dive #	Date	Time	Latitude (°N)	Longitude (°W)	Depth (m)	Material	Description
EX1502L3	Pichincho	3	12-Apr-2015	14:07:55	18.3778	−67.77831	594.5	Plastic	Plate
EX1502L3	Pichincho	3	12-Apr-2015	15:35:25	18.37796	−67.7775	529.1	Metal	Soda Can
EX1502L3	Pichincho	3	12-Apr-2015	17:34:56	18.37749	−67.77593	475.3	Fabric	Fabric
EX1502L3	Pichincho	3	12-Apr-2015	17:50:26	18.37774	−67.77575	457.9	Glass	Glass Bottle
EX1502L3	Mona Canyon- West Wall	4	13-Apr-2015	15:19:12	18.75002	−67.55252	3912.5	Unknown	Unknown
EX1502L3	Mona Canyon- West Wall	4	13-Apr-2015	15:33:29	18.74989	−67.55295	3896.9	Unknown	Unknown
EX1502L3	Mona Canyon- West Wall	4	13-Apr-2015	16:51:59	18.74785	−67.55643	3673.1	Plastic	Rubber Glove
EX1502L3	Mona Canyon- West Wall	4	13-Apr-2015	18:05:43	18.74577	−67.56011	3446.3	Metal	Aluminum Can
EX1502L3	Platform	6	15-Apr-2015	13:09:29	18.15049	−67.52151	581.3	Metal	Aluminum Can
EX1502L3	Platform	6	15-Apr-2015	14:02:27	18.15103	−67.52158	565.2	Metal	Wire
EX1502L3	Platform	6	15-Apr-2015	14:28:58	18.15139	−67.52122	553.9	Fabric	Twine
EX1502L3	Guayanilla Canyon	7	16-Apr-2015	12:27:29	17.76085	−66.7587	2097.6	Metal	Sheet Metal
EX1502L3	Guayanilla Canyon	7	16-Apr-2015	12:32:27	17.76105	−66.75813	2083.9	Metal	Metal
EX1502L3	Guayanilla Canyon	7	16-Apr-2015	20:09:29	17.76750	−66.75101	1758.5	Metal	Metal Paint Bucket
EX1502L3	Pinnacles	10	27-Apr-2015	13:21:59	17.67629	−64.52526	857.0	Plastic	Fishing Line
EX1502L3	Pinnacles	10	27-Apr-2015	13:24:29	17.67627	−64.52525	857.0	Mixed	Fishing Gear
EX1502L3	Pinnacles	10	27-Apr-2015	13:26:27	17.67623	−64.52521	857.0	Mixed	Airdrop Hydrophone or Fishing Gear
EX1502L3	Pinnacles	10	27-Apr-2015	13:36:29	17.67618	−64.52542	866.0	Plastic	Plastic
EX1502L3	Exocet Seamount	11	28-Apr-2015	13:37:52	18.03023	−64.32809	2895.1	Metal	Tomato Can
EX1502L3	Exocet Seamount	11	28-Apr-2015	13:49:57	18.03020	−64.32838	2887.9	Unknown	Unknown
EX1502L3	Exocet Seamount	11	28-Apr-2015	13:54:49	18.03025	−64.3284	2887.7	Metal	Metal Can
EX1502L3	Exocet Seamount	11	28-Apr-2015	13:56:29	18.03028	−64.32844	2888.1	Metal	Metal Barrel
EX1502L3	Exocet Seamount	11	28-Apr-2015	14:17:26	18.02984	−64.32931	2811.9	Metal	Metal Barrel
EX1502L3	Whiting Seamount	12	29-Apr-2015	14:23:59	17.84416	−65.7	1091.9	Plastic	Plastic
EX1502L3	Whiting Seamount	12	29-Apr-2015	15:38:58	17.84238	−65.69981	927.9	Metal	Can
EX1502L3	Whiting Seamount	12	29-Apr-2015	19:17:56	17.83554	−65.69295	537.4	Metal	Can Top
EX1502L3	Whiting Seamount	12	29-Apr-2015	19:27:55	17.83524	−65.69236	528.5	Mixed	Parachute and Gear
EX1811	Trough South Wall	5	05-Nov-2018	18:27:27	17.77268	−65.42583	1937.2	Plastic	Plastic Pipe
EX1811	Isla Caja de Muertos	7	07-Nov-2018	17:40:57	17.82448	−66.56722	530.9	Glass	Glass Bottle
EX1811	Isla Caja de Muertos	7	07-Nov-2018	18:11:37	17.82487	−66.56669	513.9	Plastic	Plastic Bottle
EX1811	Isla Caja de Muertos	7	07-Nov-2018	20:18:54	17.82582	−66.56589	430.8	Metal	Cable
EX1811	Isla Caja de Muertos	7	07-Nov-2018	21:12:43	17.8269	−66.56541	406.6	Fabric	Red/Pink Fabric
EX1811	Isla Caja de Muertos	7	07-Nov-2018	21:30:30	17.82744	−66.56551	408.9	Metal	Metal Pipes
EX1811	Mona Canyon West Wall	10	10-Nov-2018	14:25:00	18.75144	−67.58714	2763.9	Metal	Metal
EX1811	Mona Canyon West Wall	10	10-Nov-2018	14:35:00	18.75154	−67.58753	2753.6	Metal	Metal
EX1811	Mona Canyon West Wall	10	10-Nov-2018	15:30:00	18.75186	−67.58916	2652.5	Metal	Metal Canister
EX1811	Mona Island Escarpment	13	13-Nov-2018	16:25:00	18.20707	−67.80236	419.1	Metal	Metal

(*continued on next page*)

Table 1 (*continued*)

Expedition	Dive Site	Dive #	Date	Time	Latitude (°N)	Longitude (°W)	Depth (m)	Material	Description
EX1811	North of Bajo de Sico	14	14-Nov-2018	19:23:40	18.29056	−67.45953	392.3	Mixed	Paintbrush
EX1811	North of Bajo de Sico	14	14-Nov-2018	19:54:07	18.29133	−67.45951	362.1	Metal	Metal Fishing Weight
EX1811	North of Bajo de Sico	14	14-Nov-2018	20:06:27	18.29163	−67.45943	354.6	Plastic	Fishing Line
EX1811	North of Bajo de Sico	14	14-Nov-2018	21:35:00	18.29268	−67.46055	324.1	Metal	Cable
EX1811	North of Bajo de Sico	14	14-Nov-2018	21:50:00	18.29295	−67.46088	321.5	Metal	Fishing Weight
EX1811	Pichincho Wall East	15	15-Nov-2018	15:02:32	18.37074	−67.755	322.8	Metal	Metal Rod
EX1811	Pichincho Wall East	15	15-Nov-2018	17:36:42	18.37147	−67.75552	250.9	Fabric	Cloth
EX1811	Pichincho Wall East	15	15-Nov-2018	17:50:25	18.37151	−67.75579	255.3	Plastic	Fishing Line
EX1811	Pichincho Wall East	15	15-Nov-2018	18:03:12	18.37163	−67.75599	251.3	Plastic	Fishing Line
EX1811	Pichincho Wall East	15	15-Nov-2018	18:42:31	18.37164	−67.57691	251.4	Fabric	Black Fabric
EX1811	Pichincho Wall East	15	15-Nov-2018	19:05:00	18.37163	−67.75725	252.4	Metal	Fishing Weight
EX1811	Pichincho Wall East	15	15-Nov-2018	19:25:00	18.37168	−67.75766	253.2	Metal	Rebar
NF2202	Guayanilla Canyon	GEX-22-04	12-Apr-2022	16:36:22	17.8968	−66.7183	655.0	Unknown	Unknown
NF2202	Guayanilla Canyon	GEX-22-04	12-Apr-2022	16:40:06	17.8968	−66.7183	653.0	Metal	Metal Can
NF2202	Guayanilla Canyon	GEX-22-04	12-Apr-2022	16:44:19	17.8968	−66.7183	652.0	Metal	Metal Can
NF2202	Guayanilla Canyon	GEX-22-04	12-Apr-2022	17:00:03	17.8968	−66.7183	639.0	Unknown	Bag
NF2202	Guayanilla Canyon	GEX-22-04	12-Apr-2022	17:02:31	17.8968	−66.7183	637.0	Mixed	Debris Pile
NF2202	Guayanilla Canyon	GEX-22-05	14-Apr-2022	13:51:46	17.9154	−66.7044	524.0	Unknown	Unknown
NF2202	Grappler Bank	GEX-22-07	14-Apr-2022	15:07:40	17.8077	−65.9586	563.0	Glass	Glass Bottle
AT50-02	Main Ridge	AL5088	27-Jul-2022	17:58:45	19.36844	−65.35221	6047.1	Metal	Metal debris
AT50-02	Main Ridge	AL5088	27-Jul-2022	17:59:20	19.36833	−65.35209	6047.1	Metal	Metal debris
AT50-02	Main Ridge	AL5088	27-Jul-2022	18:00:52	19.36807	−65.35185	6047.1	Metal	Metal Can
AT50-02	Main Ridge	AL5088	27-Jul-2022	18:03:43	19.36759	−65.35138	6047.1	Fabric	Burlap Sack
AT50-02	Main Ridge	AL5088	27-Jul-2022	18:11:04	19.367	−65.35099	6047.1	Metal	Metal Ladder
AT50-02	Main Ridge	AL5089	29-Jul-2022	17:23:37	19.54303	−65.57186	6047.6	Metal	Can
AT50-02	Main Ridge	AL5089	29-Jul-2022	18:08:33	19.54732	−65.56855	5952.0	Glass	Brown Glass Beer Bottle
AT50-02	Main Ridge	AL5089	29-Jul-2022	18:25:08	19.54846	−65.56794	5910.8	Glass	Glass Jar
AT50-02	Main Ridge	AL5089	29-Jul-2022	18:41:35	19.5487	−65.56789	5902.5	Metal	Tin Can
AT50-02	North Wall	AL5090	30-Jul-2022	15:34:17	20.29442	−65.70558	6301.4	Unknown	Box
AT50-02	North Wall	AL5090	30-Jul-2022	17:34:09	20.29784	−65.70487	5844.6	Mixed	Mixed Debris Pile
AT50-02	South Wall	AL5092	1-Aug-2022	15:05:55	18.82953	−66.46277	3689.7	Unknown	Unknown
AT50-02	South Wall	AL5092	1-Aug-2022	15:11:40	18.82925	−66.46374	3698.2	Glass	Glass Bottle
AT50-02	South Wall	AL5092	1-Aug-2022	15:15:27	18.82902	−66.4642	3691.0	Unknown	Unknown
AT50-02	South Wall	AL5092	1-Aug-2022	15:50:13	18.83177	−66.45765	3674.4	Unknown	Unknown
EX2206	Lang Bank	7	29-Aug-2022	15:49.45	17.8435	−64.44072	591.7	Glass	Glass Jar
EX2206	Lang Bank	7	29-Aug-2022	15:51.21	17.84345	−64.44066	588.2	Glass	Glass Bottle
EX2206	Lang Bank	7	29-Aug-2022	14:58:45	17.84444	−64.44087	629.5	Glass	Glass Jar

(*continued on next page*)

Table 1 (*continued*)

Expedition	Dive Site	Dive #	Date	Time	Latitude (°N)	Longitude (°W)	Depth (m)	Material	Description
EX2206	Lang Bank	7	29-Aug-2022	15:19:29	17.84412	−64.44069	615.0	Glass	Glass Bottle
EX2206	Lang Bank	7	29-Aug-2022	15:40:59	17.84384	−64.44081	605.6	Glass	Glass Bottle
EX2206	Lang Bank	7	29-Aug-2022	15:45:59	17.84364	−64.44072	597.6	Glass	Glass Bottle
EX2206	Lang Bank	7	29-Aug-2022	15:59:59	17.84318	−64.44088	578.3	Glass	Glass Bottle
EX2206	Lang Bank	7	29-Aug-2022	16:16:58	17.84289	−64.44075	565.9	Metal	Container With Metal Lid
EX2206	Lang Bank	7	29-Aug-2022	16:27:29	17.84249	−64.4407	549.8	Unknown	Dish
EX2206	Lang Bank	7	29-Aug-2022	17:07:14	17.84168	−64.44068	510.3	Plastic	Plastic Fishing Equipment
EX2206	Lang Bank	7	29-Aug-2022	17:07:14	17.84168	−64.44068	510.3	Plastic	Plastic Container
EX2206	Lang Bank	7	29-Aug-2022	17:07:14	17.84168	−64.44068	510.3	Metal	Tin Can
EX2206	Lang Bank	7	29-Aug-2022	17:32:28	17.84125	−64.44056	488.1	Plastic	Plastic Gargabe Can
EX2206	St. Croix	8	30-Aug-2022	13:17:59	17.58094	−64.8726	609.4	Metal	Metal Can
EX2206	St. Croix	8	30-Aug-2022	13:17:59	17.58094	−64.8726	609.4	Metal	Metal Can
EX2206	St. Croix	8	30-Aug-2022	13:17:59	17.58094	−64.8726	609.4	Metal	Metal Can
EX2206	St. Croix	8	30-Aug-2022	13:19:59	17.581	−64.87254	610.2	Metal	Metal Can
EX2206	St. Croix	8	30-Aug-2022	15:06:52	17.58265	−64.87056	517.6	Metal	Metal Cylinder
EX2206	St. Croix	8	30-Aug-2022	17:23:02	17.5842	−64.86944	456.4	Plastic	Fishing Net
EX2206	St. Croix	8	30-Aug-2022	17:28:11	17.58428	−64.86931	448.5	Unknown	Bag
EX2206	St. Croix	8	30-Aug-2022	18:00:26	17.58447	−64.86904	429.9	Glass	Glass Bottle
EX2206	Main Ridge	9	31-Aug-2022	15:51:17	19.3635	−65.32929	5994.8	Unknown	Can, Possibly Metal
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:34	19.36407	−65.329	5953.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:42	19.364	−65.329	5951.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:42	19.364	−65.329	5951.3	Unknown	White Unknown Fragments
EX2206	Main Ridge	9	31-Aug-2022	16:42	19.364	−65.329	5951.3	Unknown	White Unknown Fragments

et al. (2019) for detailed discussion of ROV Deep Discoverer dive track estimation. Navigation files from EX1502L3 Dive 2 were not available, so this dive is excluded from the density analysis. Trash densities were not estimated for other dives because cameras were not always recording the seafloor throughout the dive due to varied scientific objectives. We compared the continuous variables of trash densities and maximum dive depth using a Spearman rank correlation because Shapiro-Wilk tests indicated that these data were not normally distributed. Because none of these dives were systematic transects covering a set area at a fixed altitude, trash densities reported in Supplementary Table 1 are estimates and should be treated as such.

3. Results

We observed a total of 139 pieces of marine litter in deep waters around Puerto Rico (Table 1, Fig. 1). Debris was diverse in material and origin, including aluminum cans, glass bottles, clothing, a ladder, and multiple types of plastic trash (Table 1, Fig. 2, Supplementary Fig. 1). The most abundant material observed was metal (48 items), followed by plastic (29), glass (16), mixed materials (7), fabric (7), wood (1). The material type of 31 observed items was not able to be determined from visual inspection. At least ten debris items were believed to originate from fishing gear, including fishing line, weights, and netting.

Debris was found from 250 to 6300 m. The number of trash observations varied by dive, with some dives having few pieces of marine

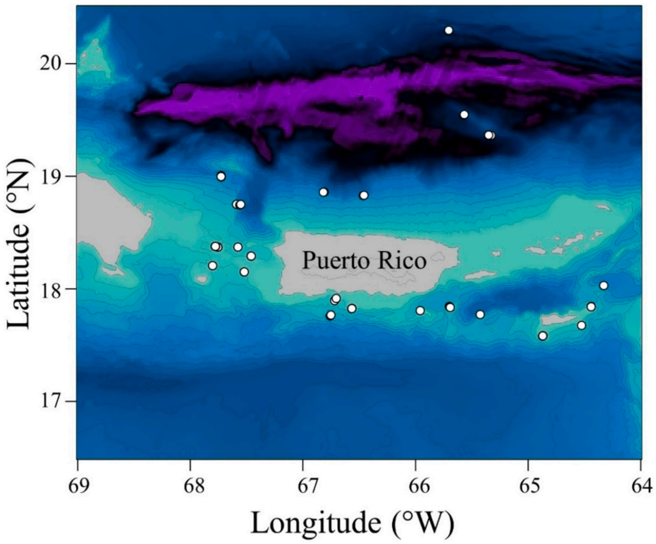

Fig. 1. Deep-water locations around Puerto Rico where trash was observed in the present study. Data were collected on expeditions EX1502L3, EX1811, EX2206 (NOAA Ship *Okeanos Explorer*), NF2202 (NOAA Ship *Nancy Foster*), and AT50-02 (RV *Atlantis*).

litter and others having up to 21 unique observations (Table 1). The composition of materials observed did not significantly vary by dive depth (ANOSIM, Bray-Curtis dissimilarity, 999 permutations, $R = 0.1233$, $p = 0.175$). Estimated trash densities ranged from 38 to 4318 pieces of debris per km^2 (median 293, mean 545 pieces of trash per km^2; Supplementary Table 1). Depth also did not significantly predict the estimated density of trash (Spearman rank correlation, $r = -0.2145923$, $S = 991.11$, $p = 0.2041$, $n = 16$, Supplementary Table 1). However, the deepest dive for which trash density could be estimated (EX2206, Dive 9) had considerably more trash per area observed than all other dives, with an estimated 4318 pieces of trash per km^2 (Supplementary Table 1). In only 1 h of seafloor observation time, 11 pieces of trash were observed on this dive, which had a maximum depth of 6012 m.

Deep-sea organisms were regularly observed interacting with the trash on the seafloor. Mobile organisms such as fishes, crabs, and squat lobsters, were found swimming or crawling into glass bottles and other open debris. Benthic taxa such as anemones, crinoids, urchins, and brittle stars were often seen atop larger pieces of debris (Fig. 2, Table 1). One object with an attached parachute (Fig. 2n) had a sea urchin and two anemones on top of the canister and a fish—a roughy, *Hoplostethus* sp. —hiding inside. Other pieces of trash were found without associate organisms (Fig. 2).

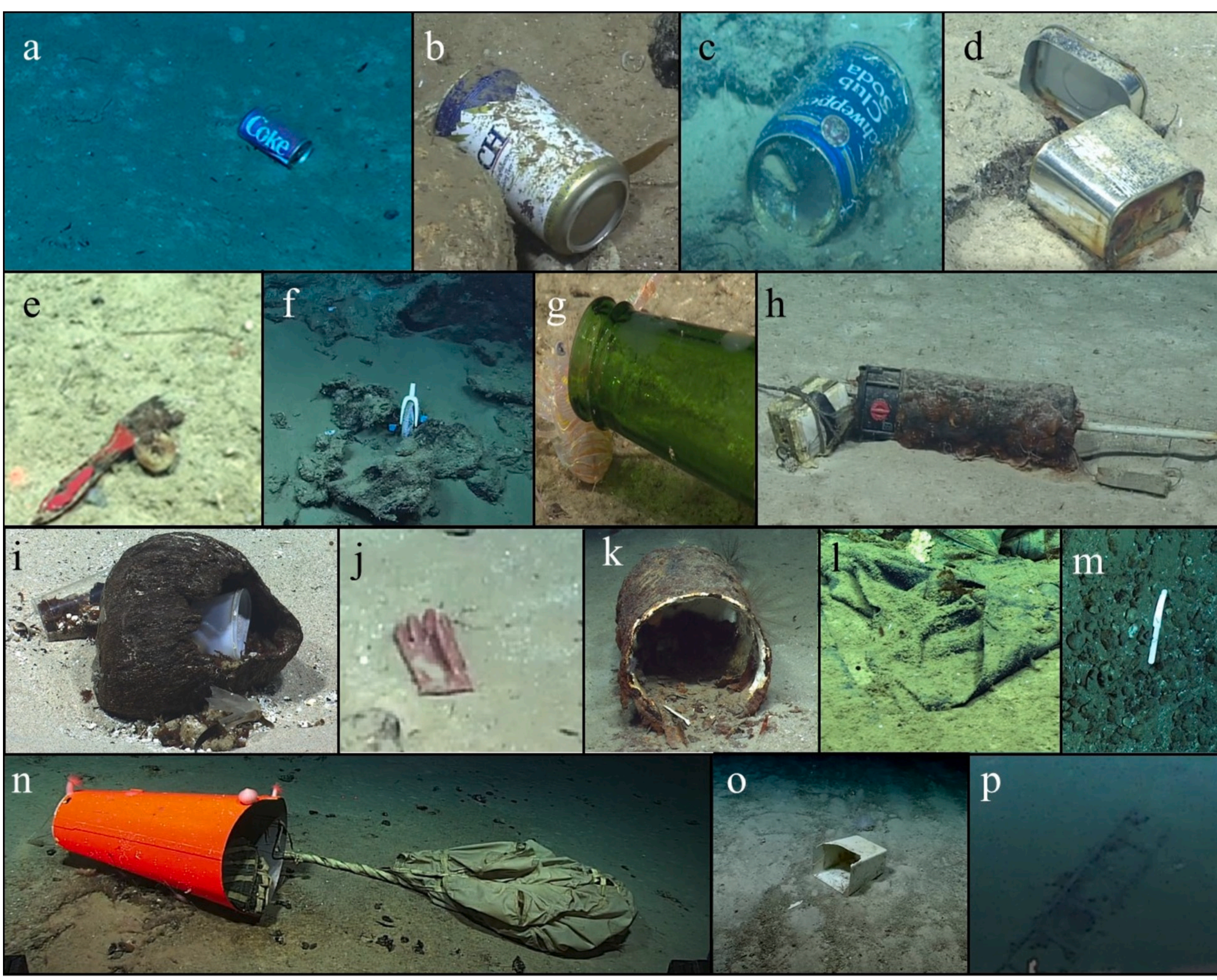

Fig. 2. Example marine litter found in deep waters off Puerto Rico. **a)** Aluminum soda can, 4058.3 m. **b)** Aluminum beer can, 3446.3 m. **c)** Aluminum club soda can, 586.9 m. **d)** Metal container, 2753.4 m. **e)** Paintbrush, 392.3 m. **f)** Bicycle tire, 629.75 m. **g)** Glass bottle with squat lobster, 457.91 m. **h)** Unknown, potentially fishing gear, 857 m. **i)** Plastic cup inside coconut with plastic cup behind, 3671.4 m. **j)** Rubber glove, 3673.1 m. **k)** Metal bucket, 1758.5 m. **l)** Denim, 4050.8 m. **m)** Plastic knife, 3501.5 m. **n)** Parachute, 528.5 m. **o)** Plastic garbage can, 488.1 m. **p)** Metal ladder, 6047.1 m.

4. Discussion

In this study, we document frequent observations of trash in the deep oceans in video surveys of the deep tropical Atlantic Ocean and Caribbean Sea. These findings demonstrate human impacts on the deep oceans, habitats that are often considered to be remote or even isolated. In many cases, these dives were the first to observe these deep-water sites, making the evidence of human waste in these habitats all the more striking.

The composition of debris in the deep ocean can provide information about the source of the material, the duration of time the trash will remain on the seafloor, and the potential impacts on marine organisms. Metal was the most commonly observed material in the present dataset, accounting for 34.5 % of debris, while plastic made up 20.9 % of the observed trash. This metal material is likely the heaviest of observed debris, suggesting a relatively nearby source (e.g., Amon et al., 2020). The second most commonly observed material in this study were plastics, which are known to make up significant portions of marine debris: 41 % in European seas surveyed (Pham et al., 2014), 56 % off Sardinia and the Tyrrhenian Sea from depths 740–1740 m (Cau et al., 2018), and 18 % in bottom trawl surveys of the Barents Sea (Grøsvik et al., 2018). These light materials can float far from land, impacting ecosystems at great distances from their sources (Amon et al., 2020; Audrézet et al., 2021; Barnes et al., 2009; Sherrington, 2016). In this study, trash was found across dive sites and depths with no observed pattern to distribution, supporting previous findings that while deep waters close to shore often have higher quantities of debris, no sites are immune from trash inputs (Amon et al., 2020; Pham et al., 2014), including in ultra-deep hadal habitats >6000 m, such as the Puerto Rico Trench (present study), the Kuril Kamchatka Trench (Fischer et al., 2015), and the Mariana Trench (Chiba et al., 2018). Identifying the origin of marine debris is a critical step toward implementing effective management and sustainability policies for ocean habitats. Imaging methods alone, such as those used in this study, are often insufficient in determining litter composition and origin. For example, the material type for 31 of the 139 observations in this study could not be identified. To address this limitation, quantitative surveys that combine both imagery and physical sampling are recommended for future work (e.g., Pham et al., 2014).

In these opportunistic observations, trash density estimates were comparable to published densities for other deep-sea regions. We estimated trash density in this region to range from 38 to 4318 pieces of debris per km^2 (Supplementary Table 1), although these estimates are based on dives with non-linear, non-random observation paths at variable altitudes. In the HAUSGARTEN observatory in the Arctic Ocean, trash densities were between 660 and 6566 pieces of trash per km^2 (Tekman et al., 2017). In the North Pacific, total debris densities were estimated to be 11–342 trash items per km^2 across depths 1085 to 6037 m (Chiba et al., 2018). In the deep Central and Western Pacific, trash densities were estimated at 0 to 9524 items per km^2, varying by distance to human-settled land, depth, and local geology (Amon et al., 2020). Off the Northeast United States in the Atlantic, estimates ranges from 200 to 13,000 trash items per km^2 (Quattrini et al., 2015), comparable to the trash density estimates from the tropical Atlantic and Caribbean Sea presented here. High trash density estimates from one Puerto Rico Trench dive in the present study suggest that marine litter could be especially abundant at hadal sites. The canyon shape of deep-sea trenches is believed to funnel organic material (e.g., Itoh et al., 2011; Ichino et al., 2015). These same physical processes could also carry debris to great depths. Future efforts should determine trash abundances using quantitative scientific transects at fixed altitude to understand depth-related patterns in trash distribution.

Although we were not able to directly assess the effects of the observed trash on the communities surveyed here, marine debris is known to impact organisms across taxa. Debris such as plastic and fishing gear presents entanglement and choking hazards for marine megafauna. A recent literature review (Gall and Thompson, 2015) found reports of 44,006 individuals of 395 different species that had ingested or been entangled in marine debris, with plastic being the most reported encounter material. Seventeen percent of species that ate or became entangled in marine debris are listed as near threatened, vulnerable, endangered, or critically endangered on the IUCN Red List (Gall and Thompson, 2015). Some debris in the present study (~7 %), was related to fishing, including nets and line. Fishing-related debris is known to be abundant in the deep ocean (e.g., 34 % of debris surveyed by Pham et al., 2014; 18.3 % of debris surveyed by Amon et al., 2020). This gear can continue to entangle organisms after being lost. For example, in the deep Mediterranean Sea, multiple dead organisms such as *Geryon* crabs were found in fishing gear that had sunk to the seafloor (Ramirez-Llodra et al., 2013). Off the northeastern United States, multiple instances of deep-sea corals being entangled in debris have also been observed (e.g. Quattrini et al., 2015). In some cases, derelict gear was entangled on dead coral colonies, demonstrating negative impacts of trash on long-lived and vulnerable deep-sea taxa (Quattrini et al., 2015). Marine debris also has the potential to impact ecosystems through the transport of pathogens and invasive species (Audrézet et al., 2021).

Further, debris continues to impact marine organisms as it degrades over time. As plastics break down due to mechanical and chemical processes, they form microplastics, plastic particles <5 mm in size (e.g., Arthur et al., 2009). These microplastics are believed to be increasing in concentration in marine systems as larger plastic waste breaks down (Barnes et al., 2009). Microplastics enter the deep ocean not only through direct sinking, but through rapid transport by particle feeders such as larvaceans (Choy et al., 2019). Deep-sea sediments accumulate these microplastics, resulting in abundances significantly higher than those found in surface waters (Woodall et al., 2014). These microplastics are ingested by marine organisms, including hadal amphipods living in the deepest ocean depths (Jamieson et al., 2019). Although the physiological impacts of microplastic ingestion remain to be studied in deep-sea organisms, in shallow waters these materials are known to harm organisms by directly blocking or damaging digestive tracts and feeding structures and through the leaching of toxins into the organism after digestion (e.g., Arthur et al., 2009). In addition to the plastic itself, additives such as brominated diphenyl ethers, bisphenol A, and phthalates are also transferred to marine organisms upon ingestion of microplastics. These additives have high potential for toxic effects on marine species, highlighting a poorly understood impact of plastic pollution (Hermabessiere et al., 2017). Given this evidence that marine debris harms marine organisms, the trash observations in tropical Atlantic and Caribbean deep-sea ecosystems suggest the potential for negative impacts and requires further investigation.

In conclusion, we show that marine debris is prevalent in the deep waters of the tropical Atlantic Ocean and Caribbean Sea. Trash in this region spans shelf, bathyal, abyssal, and hadal depths deeper than 6000 m. Our findings add to growing evidence that the deep oceans are acting as sinks for anthropogenic debris, even in unexplored or poorly known areas with little or no regular human presence (e.g., Amon et al., 2020; Chiba et al., 2018; Ramirez-Llodra et al., 2013; Woodall et al., 2014, 2015).

Disclaimer

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce. Any use of trade, product, or company names is for descriptive purposes of the methodology used only and does not imply endorsement by NOAA or the US Government.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Adam Soule reports financial support was provided by the National Science Foundation. Mackenzie Gerringer, Andrea Quattrini reports financial support was provided by NOAA Ocean Exploration. Mackenzie Gerringer reports that funding was provided by the National Marine Sanctuary Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117182.

Data availability

Data collected in this manuscript are presented in Table 1. The original videos collected by the *NOAA* Ocean Exploration program are available online, open access: https://data.oceannetworks.ca/ExpeditionManagement. Videos from the other expeditions are available upon request.

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